

Simulating the evolution of disc galaxies in a group environment. II. The influence of close-encounters between galaxies

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ABSTRACT

We study the evolution of disc galaxies in group environments under the effect of both the global tidal field and close-encounters between galaxies, using controlled N -body simulations of isolated mergers. We find that close-range encounters between galaxies are less frequent and less damaging to disc galaxies than originally expected, since they mostly occur when group members have lost a significant fraction of their initial mass to tidal stripping. We also find that group members mostly affect disc galaxies *indirectly* by modifying their common global tidal field. Different initial orbital parameters of group members introduce a significant “scatter” in the evolution of general properties of disc galaxies around a “median” evolution that is similar to when only the effect of the global tidal field is included. Close-encounters introduce a high variability in the properties of disc galaxies, even *slowing* their evolution in some cases, and could wash out correlations between galaxy properties and the group total mass. The combined effect of the global tidal field and close-encounters appears to be inefficient at forming/enhancing central stellar bulges. This implies that bulges of S0 galaxies should be mostly composed by young stars, which is consistent with recent observations.

Key words: galaxies: evolution – galaxies: structure – galaxies: interactions – methods: N-body simulations

1 INTRODUCTION

Galaxies experience different environments during their lifetimes, inhabiting regions of the Universe ranging in density from “average” to medium and high in environments such as groups and clusters of galaxies (e.g., Lacey & Cole 1994; Zhao et al. 2003; Berrier et al. 2009; McGee et al. 2009).

In these regions galaxies evolve under the influence of a combination of environmental and internal processes. Galaxies infalling onto a halo experience the effects of the global tidal field of their host (e.g. Gnedin 2003) which can vary gradually in intensity along their orbits or more abruptly if the halo grows rapidly or the galaxy’s stellar mass grows significantly after accretion (e.g Neistein et al. 2011). Galaxies can also experience gravitational interactions with other halo galaxies or substructures in the form of direct mergers or close-encounters with low/high relative velocity (Moore et al. 1996; Mastropietro et al. 2005). For galaxies in dense environments, both the cold and hot re-

serves of gas can be removed hydrodynamically by the hotter intra-group or intra-cluster medium via processes such as ram-pressure stripping (Gunn & Gott 1972) and starvation (Larson et al. 1980; Balogh et al. 2009), which can limit severely the capacity of galaxies to continue forming stars after accretion. Internal galactic processes, such as gas cooling, star formation, supernovae feedback, active nuclei feedback, formation of central bars also affect the evolution of galaxies and their contributions can be triggered/affected by environmental factors.

Environmental effects are believed to play a crucial role in the evolution of galaxies in dense regions of the Universe. However, the precise mechanisms through which they affect galaxies remain unclear (see the review by Weinmann et al. 2011). They are thought to be the culprits behind the lower star formation, lower fraction of disc morphologies and redder colours observed in galaxies belonging to groups and clusters in comparison to regions of lower density (e.g., Dressler et al. 1997; Lewis et al. 2002; Gómez et al. 2003; Balogh et al. 2004; Weinmann et al. 2006; McGee et al. 2008).

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Recent studies, based on cosmological simulations combined with semi-analytic models, claim that a significant fraction of galaxies that currently reside in massive clusters have been accreted as part of galaxy groups (McGee et al. 2009; De Lucia et al. 2012, but see also Berrier et al. 2009). These results emphasise the concept of galactic “pre-processing” (Zabludoff & Mulchaey 1998; Lisker et al. 2013). In this scenario, a considerable fraction of galaxies observed at present time in clusters, have had most of their properties shaped within group environments. This highlights the importance of understanding in detail the role of the environment in the evolution of galaxies within groups.

However, theoretical studies on environmental effects within galaxy groups remain surprisingly few, while most of the theoretical effort has been largely focused on galaxies residing in either massive clusters (e.g. Moore et al. 1999; Gnedin 2003; Mastropietro et al. 2005) or in Milky Way-like haloes (e.g. Mayer et al. 2001a,b; Klimontowski et al. 2009; Kazantzidis et al. 2011). Most of the recent studies on the evolution of galaxies in group-like environments by means of observations or numerical simulations (Feldmann et al. 2011; Tonnesen & Cen 2012; Bahé et al. 2013; Bekki 2013; Taranu et al. 2013; Vijayaraghavan & Ricker 2013; Wetzel et al. 2013; Ziparo et al. 2014) have concentrated on the formation of elliptical galaxies, the effect of ram-pressure stripping on galaxies by the intergalactic medium, and on the efficiency of galaxies to form stars while they inhabit a group. Interestingly, little attention has been paid to understand better the relative contribution of different environmental (and environmentally-triggered) processes (e.g. driven by the global tidal field, close-encounters between galaxies, rapid halo growth) to the overall evolution of galaxies in groups. This is a fundamental step in order to comprehend how galaxies currently residing in massive clusters have been “pre-processed”.

Close-encounters between galaxies are considered one of the main contributors to their evolution. Within groups, these encounters take place at lower relative velocity with respect to interactions within more massive clusters. Given the long duration of the gravitational perturbation, galaxy close-encounters in groups can induce significant changes in the structure of galaxies.

Bekki & Couch (2011) investigate the combined effect of the global tidal field of groups and repetitive close-encounters on the evolution of spiral galaxies, using chemodynamical simulations. They find that the combined tidal interaction can have a significant impact on the morphology of galaxies, inducing series of bursts of star formation that increase the stellar mass in the central bulges. These results suggest that groups are suitable environments where S0 galaxies can be formed, in line with implications from observational evidence (Wilman et al. 2009; Just et al. 2010).

As mentioned above, however, the relative contribution of the global tidal field and close-encounters to the general evolution of galaxies in groups remains unclear. Group members (except the galaxy under study) are usually modelled as point mass objects. In addition, the use of standard Schechter functions for the stellar mass distribution of group members does not allow the evolution that group members experience in terms of their orbits, structure and mass content to be followed consistently, starting from stel-

lar masses consistent with recent observations. Moreover, by adopting a significantly higher number of group members in comparison to observations (as done for example in Bekki & Couch 2011), the contribution of close-encounters to galaxy evolution could be largely overestimated. All these factors are potentially relevant for the way galaxies interact with each other, and perhaps more importantly, for how galaxies might also affect the environment they inhabit. In groups, the co-evolution between a single galaxy and its environment should be more significant than in clusters, because of its larger contribution to the total mass of the environment (see Aceves et al. 2013).

In the previous paper of this series (Villalobos et al. 2012), we explore the evolution of disc galaxies within the global tidal field of a galaxy group by means of N -body simulations of isolated mergers, covering an ample parameter space of different orbits, disc inclinations, galaxy-to-group mass ratios, and presence of a central bulge. We find that the galaxy-to-group mass ratio and the initial inclination of disc galaxies at the time of accretion play a fundamental role in the evolution of galaxies within a group (see also Bekki 2013). Specifically, we find that disc galaxies start suffering significant evolution due to the global tidal field only after the mean density of the group (within the orbit of the galaxy) exceeds 0.3–1 times the disc galaxy central density. Different inclinations of disc galaxies at the time of accretion cause them to experience significantly different structural evolution. In particular, retrograde infalls (inclination of 180° with respect of their orbital plane) allow accreted galaxies to retain their initial disc structure for a significantly longer time in comparison to prograde infalls (inclination of 0°). Additionally, we find that the global tidal field of a group environment is not efficient at either inducing the formation of central bulges in stellar discs or enhancing existing ones at the time of accretion. This result suggests that the global tidal field alone cannot explain the formation of S0 galaxies in groups, and that additional processes (e.g., close-encounters, internal processes) are required to explain the formation of additional bulge stars. Finally, we find that more massive galaxies suffer more tidal stripping due to the fact that the stronger dynamical friction acting on them drags them rapidly to the densest region of the group, where they are exposed to stronger tidal forces.

In this paper, we present the results of controlled N -body simulations of infalling disc galaxies as they are accreted onto a group-size halo that contains a central galaxy and a population of satellite galaxies. We explore different orbital parameters (consistent with cosmological simulations) for the infalling disc galaxy and various spatial, velocity and mass distributions for the population of satellite galaxies. Our main goal is to determine the contribution of low-velocity close-encounters to the evolution of galaxies within a group environment. Our approach is to compare simulations of the combined influence of global tidal field and close-encounters to simulations where only the influence of the global tidal field is included.

As in the first paper of this series, our group environments are built from idealised initial conditions and do not account for hierarchical growth. In particular, our simulations do not consider cases where galaxies are accreted and

evolve as part of “sub-haloes” within a group halo¹. Note also that our simulations do not include gaseous components and star formation, since we focus on the effect of close-encounters (and the group tidal field) on the stellar content of galaxies that is *already present* at the time they are accreted onto a group environment. We plan to explore the effect of internal processes and the evolution of star formation in galaxies within groups in the next paper of this series.

The layout of this paper is as follows: Section 2 describes the set-up of our experiments; Section 3 describes our findings; in Section 4 we discuss our results and in Section 5 we give our conclusions.

2 SET-UP OF NUMERICAL EXPERIMENTS

We have carried out 113 simulations of isolated mergers between a disc galaxy and a group halo containing a population of galaxies. Our basic setup is to release a single disc galaxy at a time, on a bound orbit, from the virial radius of the larger halo, exploring its evolution for 12 Gyr. As the galaxy infalls toward the central region of the halo, dragged by dynamical friction, it suffers the effects of both the global tidal field of the group, and also of close-encounters with other galaxies within the group. Each simulation generates 192 snapshots which allow us to follow accurately the orbits, mass stripping and overall evolution of each galaxy.

2.1 Initialisation of multi-component systems

The group halo in our simulations is modelled as a N -body self-consistent multi-component system composed by a DM halo that follows a NFW density profile (Navarro et al. 1997) and a central stellar spheroid following a Hernquist density profile (Hernquist 1990). Our main haloes have a total mass of $10^{13} M_{\odot}$, following the mass range reported by McGee et al. (2009) and De Lucia et al. (2012), where significant environmental effects on galaxies must take place (see also Berrier et al. 2009). Additionally, a population of galaxies are embedded in the group halo which are also composed by both a NFW halo and a central stellar component following a Hernquist profile. In the rest of the paper, we refer to these galaxies as “group members” or “group population”. Each disc galaxy is modelled as a multi-component system with a NFW DM halo, a stellar disc following an exponential radial density profile and a *sech*² vertical density profile. In some experiments, we also include a Hernquist central stellar bulge. A detailed description of the procedure followed to initialise our systems can be found in Villalobos & Helmi (2008).

We have carried out preliminary tests to ensure the stability of each system and lack of evolution due to either particle or time resolution.

¹ De Lucia et al. (2012) estimate that about half of low ($9 < \log[M_*/M_{\odot}] < 10$) and intermediate ($10 < \log[M_*/M_{\odot}] < 11$) mass group members are accreted onto their final group when they are satellite galaxies. The remaining half being accreted while being central galaxies or isolated ones.

Table 1. Properties of the group environment.

DM Halo		
Virial mass	9.9×10^{12}	(M_{\odot})
Virial radius	329.19	(kpc)
Concentration	4.87	
Circular velocity	360.07	(km s ⁻¹)
Number particles	1.1×10^6	
Softening	0.32	(kpc)
Stellar spheroid		
Mass	10^{11}	(M_{\odot})
Scale radius	1.91	(kpc)
Number particles	5×10^5	
Softening	0.06	(kpc)

Table 2. Properties of the disc galaxy.

Labels	REF,BUL ⁽¹⁾ ,CIR,RAD,RET	
DM Halo		
Virial mass	10 ¹²	(M _⊙)
Virial radius	258.91	(kpc)
Concentration	13.12	
Circular velocity	129.17	(km s ⁻¹)
Number particles	5 × 10 ⁵	
Softening	0.35	(kpc)
Stellar disc		
Disc mass	2.8 × 10 ¹⁰	(M _⊙)
Scale-length	3.5	(kpc)
Scale-height	0.35	(kpc)
Q	2	
Number particles	10 ⁵	
Softening	0.05	(kpc)

(1): A stellar bulge is added at the centre of the disc, with $M_{\text{bulge}}=0.3M_{\text{disc}}$ and $a_{\text{bulge}}=0.2R_{\text{D}}$.

2.2 Number of group members

The number of group members in our simulations has been chosen to be consistent with observations of the average number of satellite galaxies found in haloes in the mass range $13.1 < \log M_{\text{halo}} < 13.3$ and with $^{0.1}M_r - 5 \log h < -19$, respectively, from the SDSS-DR4 ($z < 0.2$) (Yang et al. 2008). The most likely number of satellite members within these limits is found to be 3. We have, however, chosen to consider 4 satellite galaxies in our simulations in order to maximise the number of close-encounters and their effect on the disc galaxy. We have also explored the effect of 8 satellite galaxies in our simulations.

2.3 Stellar and DM mass content of group members and disc galaxies

The initial stellar mass of each group member has been randomly drawn from the conditional stellar mass function of satellite galaxies (average number of galaxies as a function of galaxy stellar mass in a DM halo of a given mass) obtained from SDSS-DR4 observations (Yang et al. 2009). This corresponds to a modified Schechter function:

Table 3. Orbital parameters of the disc galaxy.

Label	Orbit (1)	θ (2)	(V_r, V_ϕ) (3)	e (4)
REF	Prograde	0°	(0.9,0.6)	0.86
BUL	Prograde	0°	(0.9,0.6)	0.86
CIR	Prograde	0°	(0.6,1.1)	0.6
RAD	Prograde	0°	(1.2,0.3)	0.97
RET	Retrograde	180°	(0.9,0.6)	0.86

REF: Reference experiment. Most likely orbital infall. BUL: Stellar bulge added to disc in REF experiment. CIR: More “circular” orbital infall. RAD: More “radial” orbital infall. RET: Retrograde orbital infall. (1): Direction of the orbital infall with respect to the disc rotation. (2): Initial angle between the orbital and intrinsic angular momentum of the disc. (3): Radial and tangential components of the initial velocity of the disc, in units of the virial circular velocity of the group. (4): Initial orbital eccentricity.

$$\Phi_{\text{sat}}(M_*|M_h) = \phi_s^* \left(\frac{M_*}{M_{*,s}} \right)^{(\alpha_s^*+1)} \exp \left[- \left(\frac{M_*}{M_{*,s}} \right)^2 \right], \quad (1)$$

that describes the contribution of satellite galaxies to halo masses within $12.9 < \log M_{\text{halo}} < 13.2$ with $\phi_s^*=1.96$, $\alpha_s^*=-1.15$ and $\log M_{*,s}=10.67$.

The stellar mass of the disc galaxy is chosen to be comparable to that of the Milky Way’s stellar disc.

For simplicity, the same DM-to-stellar mass ratio is used for the disc galaxy and group members, $\sim 40:1$. However, in our simulations group members are initialised to resemble a galaxy population on their way to “relax” within the group halo, as opposed to an “infalling” galaxy population. To this aim, haloes of group members are initialised with *half* the DM mass corresponding to their stellar mass (i.e. with an effective DM-to-stellar mass ratio $\sim 20:1$), having effective radii that are also half their respective virial radii. This is based on our previous study of the effect of the global tidal field of groups on galaxies (Villalobos et al. 2012, see also Chang et al. 2013), which shows that infalling galaxies lose approximately half of their DM content after the first pericentric passage about the group centre.

Our tests show that larger and smaller DM-to-stellar mass ratios for group members, compared to the chosen one, lead to fewer and weaker close-encounters, respectively. More massive group members are affected more efficiently by dynamical friction, which causes them to sink earlier than the disc galaxy. This leaves little time for close-encounters to take place. On the other hand, since less massive group members are less affected by dynamical friction they have longer infall times with respect to the disc galaxy. Even though this leaves plenty of time for close-encounters, they are generally weak and cause little damage to the disc galaxy.

2.4 Initial orbital parameters of group members and disc galaxies

The orbital positions and velocities of group members are assigned after randomly replacing particles of the group DM halo with the multi-component N -body systems described

Table 4. Properties of the populations of group members.

Label	M_{DM} ($10^{10} M_\odot$)	R_{vir} (kpc)	M_{stars} ($10^{10} M_\odot$)	a_{stars} (kpc)
4g1tBA	250	351.39	7	1.834
	100	258.91	2.8	1.416
	22.6	157.71	0.634	0.932
	6.04	101.58	0.169	0.642
4g1tLO	146	293.58	4.08	1.575
	82.4	242.72	2.31	1.341
	77.0	237.27	2.16	1.316
	73.0	233.17	2.04	1.297
4g1tHI	144	292.37	4.04	1.571
	119	274.06	3.32	1.486
	107	264.65	2.99	1.443
	7.25	107.96	0.203	0.676
4g2tBA	289	368.79	8.12	1.912
	228	340.77	6.38	1.787
	137	287.55	3.84	1.548
	97.5	256.73	2.73	1.406
8g1tBA	79.6	239.95	2.23	1.329
	70.7	230.65	1.98	1.285
	59.3	217.52	1.66	1.223
	49.6	204.95	1.39	1.163
	33.2	179.28	0.930	1.038
	31.5	176.16	0.882	1.023
	26.9	167.13	0.754	0.979
	23.5	159.77	0.657	0.942

Labels follow a nomenclature that indicates the number of group members (4;8), the relative total (DM+stars) mass enclosed adding all group members (1;2) and the relative distribution of stellar mass in group members with respect to the stellar disc. This can be either less (LO) or more massive (HI), or balanced (BA). M_{DM} , M_{stars} , R_{vir} and a_{stars} indicate the DM mass, stellar mass, virial radius and Hernquist scalelength of the stellar component for each group member. DM haloes and stellar spheroids are modelled with 10^5 and 10^4 particles, respectively. The actual DM mass with which each group member is initialised corresponds to *half* the values listed (see Section 2).

above. As a first approximation, this is consistent with observations (e.g., Lin et al. 2004; Biviano & Poggianti 2010) showing that the projected number density of galaxies in clusters can be described with NFW density profiles.

Following this procedure, the spatial distribution of group members populates randomly the volume of the group halo. However, we apply a set of conditions to the random choice of initial positions (and respective velocities) for group members in order to avoid that they are initialised too close to each other, to the disc galaxy, to the centre of the group, or outside the virial radius of the group. Specifically, the initial orbital position R_i (and respective velocity) for the i th-group member is assigned only if *all* of the following conditions are simultaneously satisfied: (i) $\Delta R_{i,j} \geq (R_i^{\text{eff}} + R_j^{\text{eff}})$, (ii) $\Delta R_{i,\text{disc}} \geq (R_i^{\text{eff}} + R_{\text{disc}}^{\text{vir}})$, (iii) $R_i \geq R_i^{\text{eff}}$, and (iv) $(R_i + R_i^{\text{eff}}) \leq R_{\text{group}}^{\text{vir}}$, where $\Delta R_{i,j}$ ($\Delta R_{i,\text{disc}}$) is the separation between the centres of mass of the i -th and j -th group member (disc galaxy), and R_i^{eff} is the effective radius of the i -th group member (i.e. half its virial radius R_i^{vir}).

Before placing a group member at its assigned position, a spherical volume containing an equivalent amount of DM mass is *locally* removed from the group halo, in order to keep constant the total amount of mass of the system within the virial radius of the group. Our tests show that this removal of DM mass from the group halo does not cause significant or long-lasting perturbations to its radial density profile.

As in Villalobos et al. (2012), the initial orbital parameters of the disc galaxy are chosen to be consistent with the distribution of orbital parameters of infalling substructures at the time they cross the virial radius of their parent halo, as extracted from cosmological simulations (e.g. Benson 2005).

2.5 Parameter space coverage

Tables 1 and 2 show a list of the structural, kinematical and numerical properties of the group halo and disc galaxy used in our simulations. Note that with respect to our previous simulations on the effect of the global tidal field of groups on galaxies, we have chosen a comparatively smaller group halo for the disc galaxy under study. This deliberate choice has been taken in order to maximise the frequency and/or effectivity of close-encounters within the group halo, and their effect on the disc galaxy.

Our experiments cover a parameter space related to several properties of the disc galaxy and of the population of group members that are potentially relevant for the evolution of the disc galaxy under the combined effect of the global tidal field and close-encounters.

For the disc galaxy, we explore both prograde and retrograde infalling orbits (with respect to its direction of rotation), the most likely and extreme infall eccentricities (according to cosmological simulations), and the effect of a central stellar bulge (see Table 3).

Regarding the population of group members, we probe the effect of different number of members, total mass, and mass distribution (see Table 4).

In our simulations, we explore combinations of one aspect of the parameter space related to the disc galaxy and one related to the population of group members (in all experiments the same group halo is used). Additionally, for each combination we explore 12 different initial orbital distributions (i.e. initial positions and velocities) for the group members, satisfying the conditions described in Section 2.4. We also perform “control” simulations only with the group halo and disc galaxy (group members are not included) aiming to assess the net effect of close-encounters on the evolution of the infalling disc galaxy. Following the labels introduced in Tables 3 and 4, we refer to a given experiment using the following notation: ‘ddd’ for the “control” simulation exploring a parameter of the disc galaxy, ‘ddd.gggggg’ for a combination of parameters of the disc galaxy and the group population (and regarding all 12 initial orbital distributions explored for group members). When a specific initial orbital distribution of group members needs to be referenced, a postfix ‘n’ is added as ‘ddd.gggggg.n’. E.g., the experiment REF.4g1tBA refers to the disc galaxy infalling with the most likely orbital eccentricity onto a group with a population of group members composed by 4 satellite galaxies with a relative total mass equals to 1 and a “balanced” stellar mass distribution with respect to the stellar disc.

It is important to highlight that the total mass in *all*

experiments is kept approximately constant ($\approx 10^{13} M_{\odot}$) to facilitate the comparison with the “control” simulations.

3 RESULTS

3.1 General properties of galactic encounters

In this paper, we define an encounter between the main disc galaxy and a group member as a *local* minimum in the radial separation between their centres of mass, while both orbit within the group environment. Encounters are only registered while both the disc galaxy and a given group member retain more than 5 percent of their initial stellar mass. In this way, a disc galaxy can experience several encounters with a single group member before either of their stellar components is disrupted.

Fig. 1 shows an overview of the general properties of 235 encounters that the disc galaxy experiences with group members, combining all 12 simulations covering different initial spatial distributions of group members, for the experiment with the most likely disc galaxy’s infalling orbit (REF.4g1tBA experiment).

We find that most encounters happen relatively late in our experiments, with a most likely time of occurrence of $t \sim 6$ Gyr. This suggests that encounters take place mostly after both the main disc galaxy and group members have suffered considerable mass stripping during their infalling orbits, which limits the damage caused by encounters on the disc galaxy. Note that a smaller fraction of encounters take place early in the simulations at $t \sim 1$ Gyr. This is due to the random assignment of the initial velocities, which puts galaxies preferentially on radially inward orbits, increasing the probability of encounters in the inner regions of the group.

We find that the range of radial separation between a disc galaxy and other group members during encounters is rather broad, reaching distances of ~ 400 kpc. However, the most likely radial separation during encounters is found at ~ 50 kpc. This is ~ 25 times the scale-length of disc galaxies at the most likely time of occurrence of encounters. “Very-close” encounters (< 20 kpc) and in particular mergers between galaxies are either rare or non-existent in our simulations. This is in contradiction with the common assumption that these events are frequent in the environment of groups (See Discussion).

The distribution of relative radial velocity between galaxies during encounters peaks around $500\text{--}600 \text{ km s}^{-1}$. This shows that encounters are still relatively fast in comparison to the relative radial velocity expected in more massive clusters ($\sim 1000 \text{ km s}^{-1}$). The most likely relative velocity of encounters in our simulations is consistent with estimations of the characteristic velocity dispersion of the group halo when approximated as an isothermal sphere.

Finally, we find that the amount of *total* (DM + stellar mass) mass bound to group members during encounters tends to be rather small, $\sim 2.8 \times 10^{10} M_{\odot}$. In a typical encounter, a group member has a *total* bound mass that is comparable to the mass bound to the stellar disc galaxy at the most common time for an encounter. We shall see that this, combined with the relatively large radial separation between galaxies during encounters, contributes to weaker

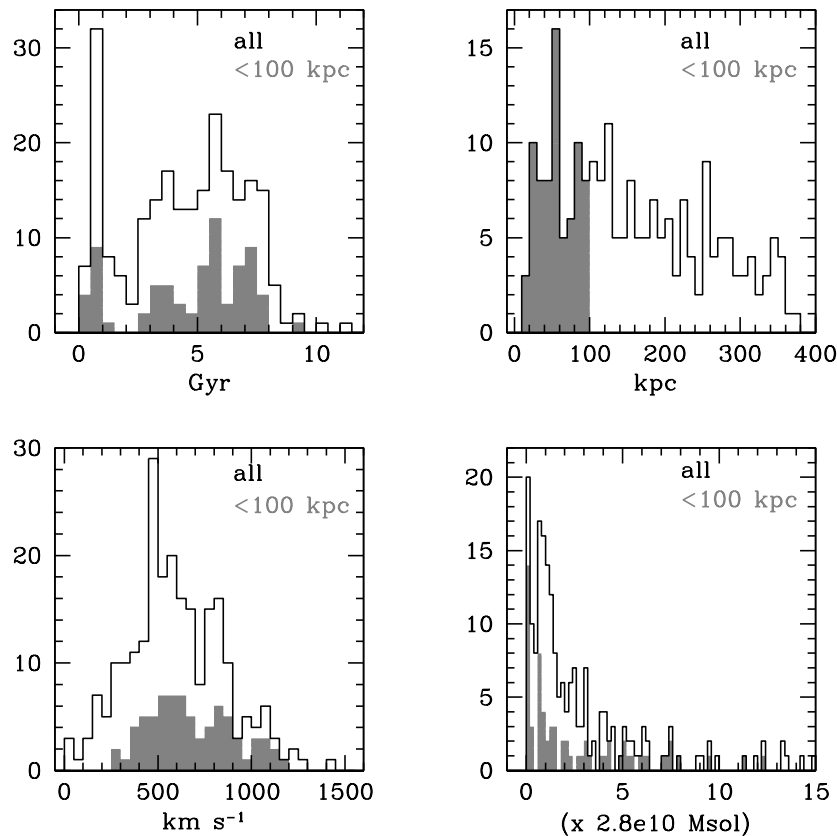


Figure 1. General properties of all the encounters between a disc galaxy and group members after it infalls with the most likely orbit. The histograms combine information from the 12 REF.4g1tBA simulations, covering different initial orbital parameters of group members. (top-left) Time of the encounters since the infall of the disc galaxy onto the group, (top-right) radial separation and (bottom-left) relative radial velocity between the disc galaxy and each group member during encounters, and (bottom-right) total mass (DM+stars) bound to each group member during encounters. Shaded areas show the properties of the subset of encounters corresponding to a radial separation from the disc centre of mass smaller than 100 kpc.

tidal forces on the disc from group members in comparison to the global tidal field.

These general properties of encounters are similar to those of the rest of our experiments, and they also apply when we restrict the analysis to “close”-encounters only, i.e. those taking place within a radial separation <100 kpc (though of course the number statistics is reduced in this case).

A parallel can be drawn with Knebe et al. (2006), although the scope and methodology of their study are different from ours. They find that penetrating encounters between DM satellites in clusters formed in cosmological simulations are also rare and have high relative velocities that are comparable to the host one-dimensional velocity dispersion. Additionally, as we shall describe in Section 3.3, they also find that most of the mass loss experienced by satellites is due to interactions with the host potential as opposed to close-encounters.

3.2 Orbital evolution of disc galaxies and separation to group members

We characterise the orbital evolution of galaxies by the evolution of the position of the centre of mass of the stellar component of galaxies, considering only stellar particles that remain bound since the beginning of the simulations (see Section 3.3).

Fig. 2 (top) shows a comparison of the orbital evolution of the disc galaxy, for 12 different initial orbital distributions of group members and 3 initial orbital eccentricities of the disc. As a reference, the orbital evolution in the respective experiments without group members is also shown. The Figure shows that the inclusion of group members affects significantly the infalling orbit of the disc galaxy. In general, interactions with group members lead to an “expansion” of the infalling orbit of the disc, independently of its initial eccentricity. Interestingly, the orbital expansion is found to be the least significant for the case of the most likely eccentricity of infall. We argue that the expansion of the infalling orbits of disc galaxies does not come as a consequence of direct interactions between the disc galaxy and the other

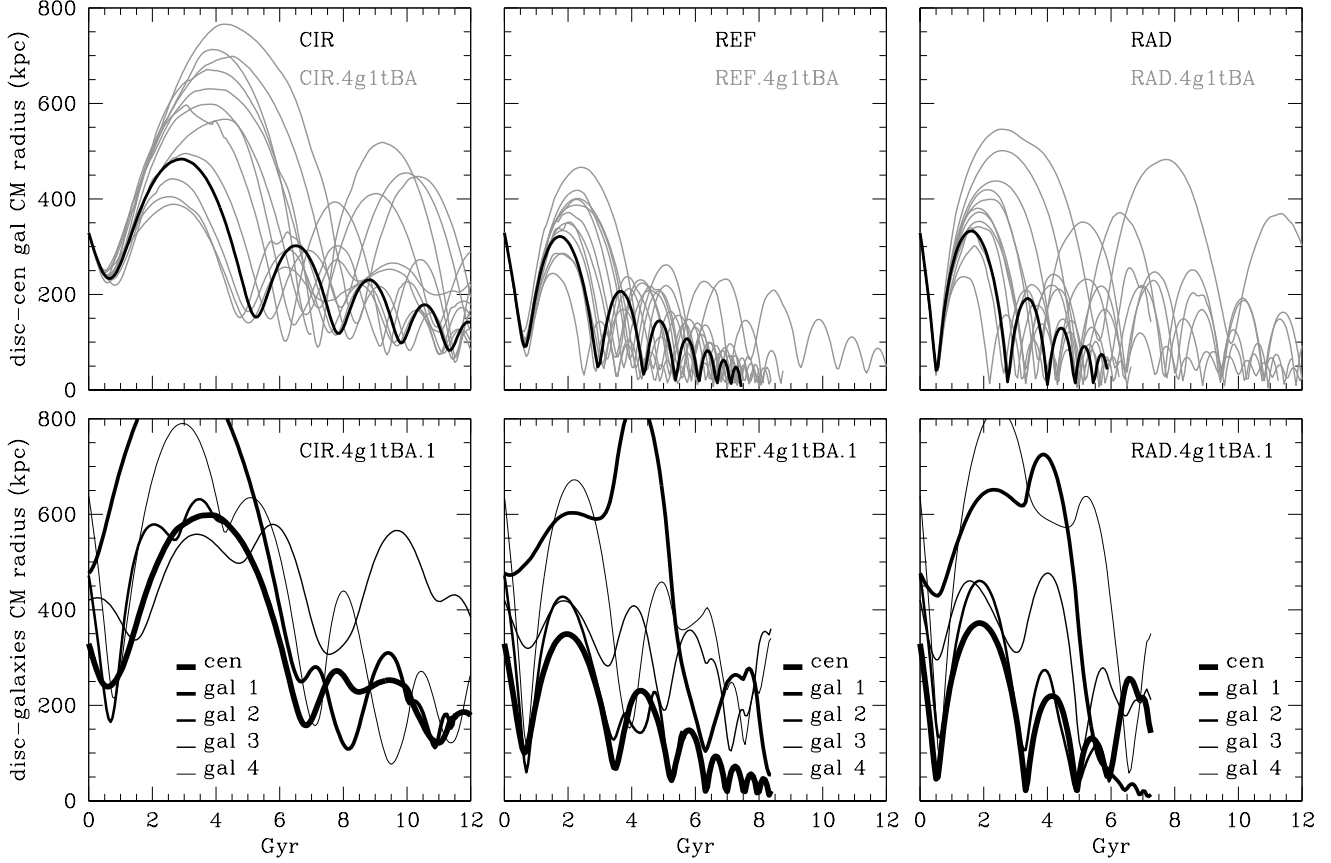


Figure 2. (top) Evolution of the radial separation between disc galaxies infalling in the group and their respective central galaxy, for increasing (initial) infalling orbital eccentricities: CIR, REF, RAD (see Table 3). Each panel shows the evolution of the (12) different initial orbital distributions for group members (grey), and the corresponding case when no members are included in the group halo (black). (bottom) Evolution of the radial separation between the disc galaxy and each galaxy in the group, for increasing (initial) infalling eccentricities and the *same* initial orbital distribution for group members. All orbits are followed until either the disc galaxy or the respective group member is disrupted.

galaxies in the systems. Instead, this is likely due to the fact that by adding a galaxy population to the group halo-disc galaxy configuration, the total energy/angular momentum of the whole system is increased. In some cases, this causes a significant displacement of the densest region of the group halo while the disc galaxy is infalling toward it. Note that the global DM density profile of group haloes only shows a negligible evolution during our simulations.

Fig. 2 (bottom) shows the typical evolution of the radial separation between the disc galaxy and the central galaxy (thickest), and the group members (thinner), for different initial infall eccentricities of the disc galaxy, and for a fixed initial orbital distribution of group members. We find that closer encounters between the disc and group members take place when the orbit of the disc is more eccentric. This is to be expected since in such orbit the pericentres of a galaxy will be smaller than in less eccentric orbits, increasing the probability that the galaxy will pass close to the centre of the group, where group members are also infalling.

3.3 Stellar stripping of disc galaxies

We quantify the stellar stripping suffered by galaxies by computing the amount of bound stellar mass that galaxies retain during their evolution within the group halo. We apply the same algorithm as in Villalobos et al. (2012). Briefly, we: (i) Consider all DM and stellar particles of the galaxy that were bound at the previous snapshot as bound at the current snapshot. If the current snapshot is the initial one, then all galaxy particles are considered bound by construction; (ii) Compute the total bound mass of the galaxy and the velocity of its centre of mass; (iii) Compute the binding energy of the particles that are considered bound using the updated velocity of the galaxy’s centre of mass; (iv) Retain only those particles that are still bound (i.e., with negative binding energy), and recompute the total mass of the galaxy; (v) If the total bound mass from (ii) and (iv) has converged, then record it and go back to (i) for the next snapshot. If the total bound mass has not converged, then go back to (ii) using the bound particles found at step (iv).

Fig. 3 shows a comparison between the median and extremes of the stellar stripping evolution suffered by disc galaxies when group members in different orbital distribu-

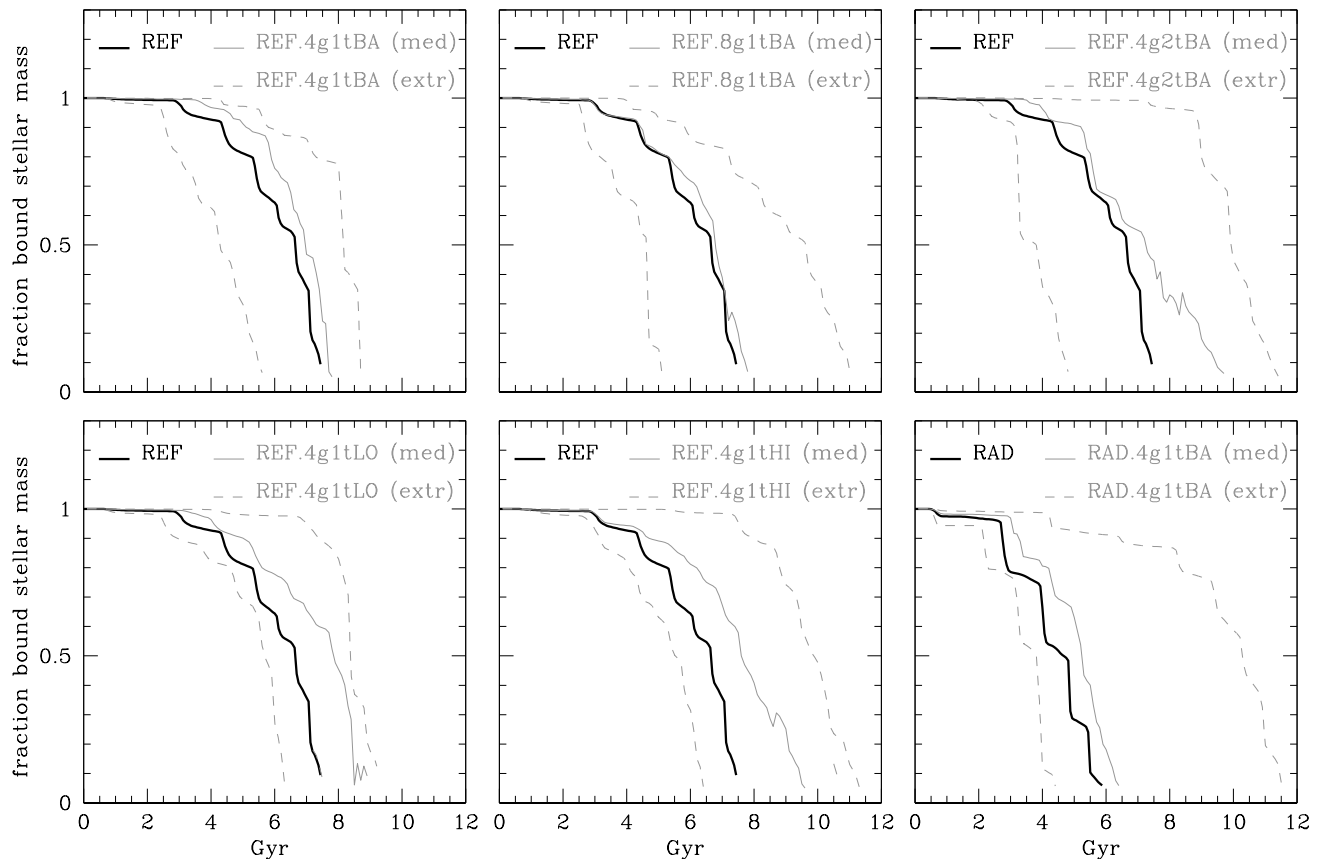


Figure 3. Evolution of the fraction of stellar mass that remains bound to disc galaxies (since their infall) in experiments covering different properties of the group population (number of members, combined total mass, mass distribution), and different (initial) infall eccentricities of disc galaxies. In each case, different initial orbital distributions of group members induce significant variations in the evolution of the fraction of stellar mass that remains bound to discs. Each panel compares the median (grey solid) and extreme cases (grey dashed) of the evolution due to the inclusion of group members to the corresponding case when no members are present in the group halo (black).

tions are included in our simulations. As a reference, the figure also shows the disc stellar stripping for the corresponding experiments when group members are not included. Note that the figure only shows experiments where the disc galaxy is disrupted before 12 Gyr of evolution. This typically excludes 1 or 2 cases in each experiment which does not affect significantly the estimation of the “median” behaviour.

We find that the inclusion of group members leads to a broad range of possible stellar stripping evolution in disc galaxies. In particular, the disruption time of identical stellar discs can vary within a range of ± 1 to ± 6 Gyr, with respect to the case when no group members are included. However, we find that the “median” stellar stripping evolution (over different initial orbital distributions for group members) can be reasonably well described by the evolution of disc galaxies in simulations where group members are not included. Even though the “scatter” in each experiment is relatively large, the lack of variation in the median evolution is encouraging for theoretical studies attempting to obtain prescriptions for stellar stripping evolution and merger timescales from controlled simulations of isolated mergers that do not account

for the effect of other galaxies (e.g. Boylan-Kolchin et al. 2008; Villalobos et al. 2013).

Interestingly, the “median” stellar stripping of stellar discs when group members are included in the experiments tends to be slower than when group members are not included. This is counter-intuitive as one would expect that close encounters accelerate the disruption of the infalling disc galaxy. The slower stellar stripping can be understood as a consequence of the “expansion” of the infalling orbit of disc galaxies, as explained in Section 3.2. This delays the orbital passages of disc galaxies around the dense central region of the group, where they are exposed to stronger tidal forces. This also highlights the fact that in our simulations stellar stripping in disc galaxies is mostly driven by interactions with the global environment (which continuously grow in mass by the disruption of group members) rather than by direct interactions between galaxies in the group (these are weak, as discussed in Section 3.1).

Note that these results are also valid for the disruption of the DM halo of disc galaxies and are similar between experiments covering different orbital eccentricities of disc galaxies, number of group members (within a factor of 2),

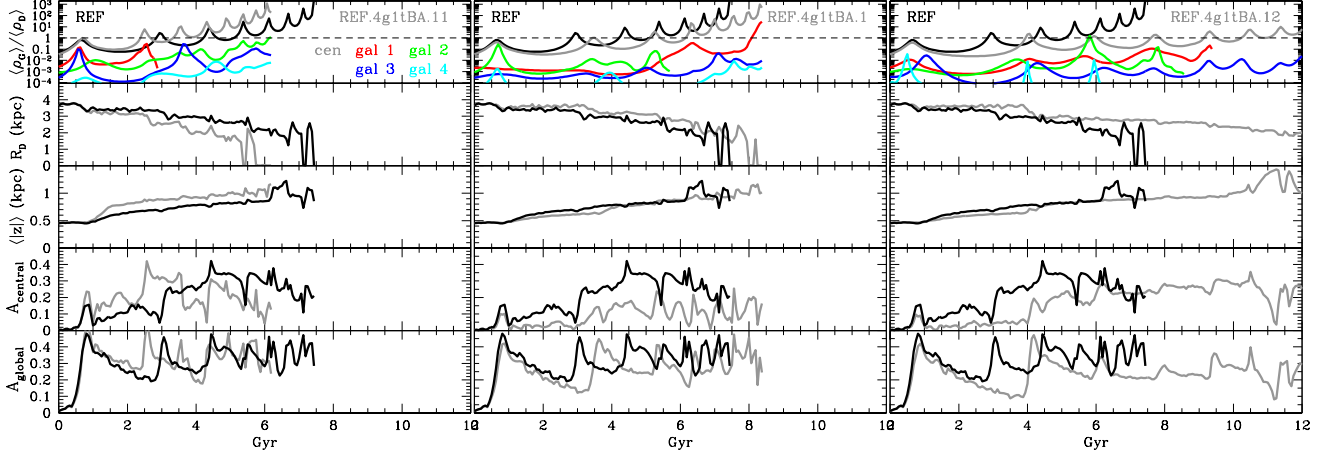


Figure 4. Examples of the different structural evolution of a disc galaxy induced *only* by different (initial) orbital distributions for group members, while keeping all other properties of the group population the same (number of members, combined total mass, mass distribution). The structural evolution of the disc, infalling with the most likely orbital eccentricity, is presented in terms of its scalelength R_D , mean thickness $\langle |z| \rangle$, and amplitude of both their central and global $m = 2$ non-axisymmetries (grey). For comparison, the structural evolution of the corresponding disc when no members are present in the group halo is also shown (black). The evolution of the “density contrast” $\langle \rho_G \rangle / \langle \rho_D \rangle$ is also included to compare the tidal forces acting on the disc galaxy due to the central galaxy (grey), each group member (coloured, in decreasing order of total mass), and when no group members are present (black). The evolution of each property is followed until either the disc galaxy or any group member is disrupted.

total mass enclosed by group members (within a factor of 2), and different stellar mass distributions for group members (being most of them either less or more massive than the stellar discs). The experiments show that the amount of “scatter” in the mass stripping mostly depends on the combined total mass of group members. This is expected since a more massive population of group members would inject a larger amount of angular momentum to the system². Note that different morphologies of infalling satellites could represent an additional source of “scatter” in their mass stripping evolution (see Chang et al. 2013). Interestingly, the case when a disc galaxy infalls in a more radial orbit is associated with an asymmetric scatter in its stellar stripping.

3.4 Structural evolution of stellar discs

As in Villalobos et al. (2012), we study the structural changes of disc galaxies as they orbit within a group environment. We start by first centring the discs on their centre of mass and aligning them in such a way that the Z-axis is defined by their rotation axes. Then, structural properties have been computed in concentric rings, 1 kpc wide (out to 20 kpc from the disc centre), considering only stars that remain bound to the disc galaxy at a given time, and that are located within 3 kpc from the midplane. We refer the

reader to Villalobos et al. (2012) for a detailed description of the procedure.

Fig. 4 illustrates the changes in the structural evolution of a disc galaxy that are introduced *only* by different (initial) orbits of group members (while keeping the same number of members, their combined total mass and mass distribution). The disc galaxy infalls with the most likely orbital eccentricity. The structural evolution of the stellar disc is shown in terms of its scale-length R_D , mean thickness $\langle |z| \rangle$, and amplitude of both central and global $m = 2$ non-axisymmetries A_{central} (bar), A_{global} (tidal arms). For comparison, the evolution of the stellar disc in the corresponding experiment without group members is included. The Figure also shows the evolution of the “density contrast” $\langle \rho_G \rangle / \langle \rho_D \rangle$, to compare the tidal forces acting on the disc galaxy due to the central galaxy and each group member. This quantity corresponds to the ratio between the mean mass density of the central galaxy (or a group member) within the distance to the disc galaxy, and the mean mass density of the disc galaxy within 10 initial scalelengths. Both mean densities only include DM and stars that remain bound at a given time. The evolution of the “density contrast” due to the central galaxy when no group members are present is also included.

We find that the inclusion of a population of group members does not have necessarily a destructive effect on the structure of the infalling disc galaxy on top of the evolution induced by the global tidal field. In fact, it is not uncommon to find that the inclusion of group members actually slows down the structural evolution of discs induced by the global tidal field. This can be seen not only in terms of the disc’s scalelength and mean thickness, but interestingly also in the reduced formation of central bars³. The Figure also shows

² Assuming a fixed group total mass, this corresponds to cases where the global DM content has a small contribution to the group total mass (see Aceves et al. 2013). Note that in these cases the variability in the properties of infalling disc galaxies is particularly high given the larger amount of angular momentum being transferred by more massive group members.

³ In the context of our simulations, the observed environmen-

that tidal forces on a disc galaxy by group members are in most cases weaker than those induced by the central galaxy. This is consistent with the description of Fig. 1, where encounters were found to be mostly distant in comparison to the extension of discs and to take place mostly after group members lose a significant amount of their initial mass content. This indicates that the global tidal field of a group plays a much more relevant role in the evolution of galaxies in comparison to that of close-encounters.

In Fig. 4 the structural evolution of discs and the estimation of tidal forces are followed only until either the stellar component of the disc galaxy or that of a group member has been disrupted. We find that identical disc galaxies (infalling with the same orbit) can survive longer, when the more massive group members also survive for a longer time. This points toward an important transfer of angular momentum from group members (especially the most massive ones) to the whole system as they are affected by dynamical friction within the group. In fact, our results suggest that the overall influence of group members on an infalling disc galaxy comes mainly indirectly by modifying the global tidal field of the group as they are disrupted, and by adding angular momentum to the whole system as they suffer dynamical friction.

Figs. A1 and A2 in the Appendix show the evolution of the scalelength and mean thickness of disc galaxies in all our experiments. We find that the median evolution can be well described by simulations that do not include group members, while the inclusion of group members introduces a significant scatter.

4 DISCUSSION

In the previous Section we have shown that, within the parameter space explored with our simulations and the assumptions we have adopted, close-encounters between galaxies in groups are rare. Additionally, according to our simulations, close-encounters in groups have a limited *direct* effect on the galaxies involved. Instead, most of the effect of group members on an infalling disc galaxy comes *indirectly* via modifications to the global tidal field of the group, as group members are tidally stripped and/or merge. Note that this implies a potentially high variability in the way a galaxy can be affected by other group members, even when only the orbital parameters of group members are different.

4.1 On correlations between galaxy properties and host halo mass

Previous studies have shown a correlation between several observables of satellite galaxies (age, metallicity, quiescent fraction), and the mass of their host haloes (e.g. Pasquali et al. 2010; De Lucia et al. 2012; Wetzel et al. 2012). These correlations are found to be relatively weak for massive satellites, while properties of less massive galaxies show a clearer dependence on host halo mass. As shown in

Section 3, even within host haloes of the same mass a particular galaxy can experience very different evolutionary paths, being strongly dependent on the evolution of other group members and how they affect their common tidal field. The high variability in the evolution of group galaxies found in our simulations would likely weaken any underlying correlation with halo properties. Even though our measurements cannot be easily translated into the observed correlations, it is striking to consider that the scatter found in our simulations could be a conservative estimation. Both rapid variations in the global potential through halo mass growth and clustered accretion of group members could further increase the scatter (see Section 4.3).

Alternatively, Hou et al. (2013) find no significant correlation between the quiescent fraction of galaxies with the dynamical mass of groups within the 10^{13} – $10^{14.5}$ M_{\odot} mass range, in catalogues from the Sloan Digital Sky Survey (SDSS), the Group Environment and Evolution Collaboration (GEEC) and the high redshift GEEC2 sample out to $z \sim 1^4$. Interestingly, they also find that the quiescent fraction is *lower* in groups *with* substructure for low mass galaxies ($\log[M_{*}/M_{\odot}] < 10.5$).

At face value, both results are consistent with the outcomes of our simulations, *if* it is assumed that stronger gravitational interactions between a galaxy and/or the global field are correlated to higher fraction of quiescent galaxies. The unclear correlation with halo mass found by Hou et al. is inline with the large “scatter” that group galaxies should exhibit in their properties according to our simulations. The lower fraction of quiescent galaxies observed by Hou et al. in groups with substructure can be understood in terms of the connection between the evolution of a given galaxy and that of other group members, as shown in Fig. 4. The Figure shows that the longer time the more massive group members/substructures survive within the group (i.e. are detectable), the less effective the global tidal field acting on an infalling galaxy is, causing it to retain its (stellar and eventually gaseous) mass content/structure for a longer time. However, it is important to highlight that, as opposed to our group members, in Hou et al. substructure lies well beyond the viral radius of the halo, which makes difficult a direct comparison of their effects.

4.2 Comparison to the effect of the global tidal field from previous simulations

4.2.1 Start of structural transformations in galaxies within groups

In Villalobos et al. (2012) we study the effect of only the global tidal field of the group environment on the evolution of galaxies, by means of controlled N -body simulations similar to those presented in this work. In our previous study, we found that accreted disc galaxies start suffering a significant structural transformation due to the global tidal field only after the mean density of the group, within the orbit of the galaxy, is ~ 0.3 – 1 times the central mean density of the galaxies. After including the effect of other galaxies in the

tal dependence between bars/bulges likelihood with environment (e.g. Skibba et al. 2012) would appear to be linked to the presence of gaseous components in group galaxies.

⁴ As stated by Hou et al., this apparent contradiction with previous studies is caused by different cuts in halo mass adopted to explore underlying correlations.

group environment, we find that this result remains a good approximation, as illustrated for a few cases in Fig. 4. This correspondence highlights the usefulness of relatively simple and less costly simulations to characterise the “mean” evolution of disc galaxies being accreted onto a group. Specifically, these results can be used to assist the implementation of particular physical processes in analytic and semi-analytic models, e.g. as done in recent studies on the formation of the intra-cluster light in hierarchical galaxy formation models (Contini et al. 2014), and on environmental influence on quenching star formation (Hirschmann et al. 2014, submitted).

4.2.2 On the formation of S0 galaxies in groups

In Villalobos et al. (2012) we also find that the global tidal field of a group alone is inefficient at either inducing the formation of central bulges in pre-existing stellar discs (i.e. in place before the accretion onto the group) or enhancing pre-existing bulges. These results can have important implications for the formation of S0 galaxies in group environments. S0 galaxies are characterised by having little gas content, practically no signs of spiral arms, and often a prominent central bulge. Their formation processes is currently unknown, although they are usually considered to be the end product of spiral galaxies affected by environmental processes (Dressler 1980; Solanes & Salvador-Sole 1992; van Dokkum et al. 1998). Increasing observational evidence points toward the group environment as the characteristic environment for the formation of these galaxies (Wilman et al. 2009; Just et al. 2010). In Villalobos et al. we concluded that, if S0 galaxies are preferentially formed in group environments, then their prominent bulges could not be produced by the effect of group tidal forces alone. This implies that bulges of S0 galaxies formed in groups would be composed mostly by young stars. In this study, we show that also the combined effect of global tidal field and close-encounters is not efficient at inducing/enhancing bulges of old stars in stellar discs. This is illustrated for a few cases in Fig. 4 in terms of the amplitude of central instabilities (also confirmed by examining the evolution of the surface density profiles of each galaxy in our experiments). It is interesting to note that the effect of other group members can actually inhibit/delay the formation of central instabilities in comparison to the effect of the global tidal field (Section 3.4). The implications of our simulations are consistent with recent observational evidence based on absorption-line index gradients (Bedregal et al. 2011) and spectroscopic bulge-disc decomposition (Johnston et al. 2012) for a sample of S0 galaxies in the Fornax cluster, indicating that in those galaxies bulges are younger than the stellar discs⁵.

⁵ However, most of well spectro-photometrically studied S0 galaxies are high mass ones, which might have a different formation path with respect to low mass satellite S0 galaxies, as shown by Wilman & Erwin (2012); Wilman et al. (2013).

4.2.3 On prescriptions of merger timescales for galaxies within groups

By means of isolated controlled simulations of mergers similar to those presented in this study, Villalobos et al. (2013) introduce a modification to the prescription of merger timescales obtained by Boylan-Kolchin et al. (2008) from comparable simulations. This modification consists in the inclusion of an explicit dependence on the redshift at which a galaxy is accreted onto a host halo and it is motivated by the evolution of halo concentration with redshift. The modified prescription offers an improvement up to $\sim 20 t_{\text{dyn}}$ in the prediction of merger timescales up to $z = 2$, in absence of interactions with other substructures.

In Fig. 3 we show that, when the effect of close-encounters with other group members are included in the simulations, the “median” stellar mass loss of a galaxy (over experiments with different initial orbital parameters for otherwise the same set of group members) can be reasonably well approximated by the mass loss experienced by the same galaxy only under the influence of the global tidal field of the group. This shows that when close-encounters are included in the simulations, the “median” merger time of a galaxy can be well predicted by a relatively simple prescription based only on the effect of the global tidal field (and dynamical friction). The inclusion of other group members introduces a dispersion, which appears to be mostly a function of the total mass of the galaxy population (or the corresponding global DM contribution to the group total mass), their mass distribution, and number of members. Such a dispersion could be introduced in galaxy formation models to explore its effect. Presumably, this would increase the scatter of predicted properties for group galaxies.

4.3 Caveats

Regarding the initial conditions adopted for our simulations, disc galaxies resemble both in mass and radial extension a slightly less massive Milky Way-like galaxy at $z=0$. Instead the radial extension (and concentration) of the DM halo of the group environment for its quoted virial mass resembles a halo at $z=1$. This configuration is set by design as we have attempted to maximise the effect of close-encounter between galaxies by placing them in a relatively smaller volume. Note however that the structure of the simulated group is still within ranges that are consistent with cosmological simulations. We have also carried out test simulations after scaling the properties of *both* disc galaxies and the group DM halo at several redshifts, obtaining an even smaller effect on the evolution of galaxies due to close-encounters.

Our simulations do not account for the hierarchical mass growth that the group DM halo might experience after the disc galaxy under study has been accreted. In this way we do not consider possible rapid variations in the global potential due to the accretion of massive substructure. In addition, by assigning random positions and velocities to group members within a halo, our simulations could oversmooth the distribution of galaxies, thereby reducing the effect of close encounters. We estimate that the effect of hierarchical mass growth of the group halo on the properties of the disc galaxy would be similar to the effect introduced by the inclusion of group members in the simulations. That

is, accreted substructure would modify the global tidal field of the group by either adding mass to its centre via mergers and/or by adding energy/angular momentum to the system. Depending on the mass of the accreted substructure, this would translate into an additional “scatter” in the evolution of the properties of galaxies around the “median” evolution expected within a group halo that does not contain other galaxies and does not experience mass growth.

Finally, our simulations do not consider cases where galaxies are accreted as part of “sub-groups” onto a group halo, as it would be expected in the context of hierarchical evolution of galaxy haloes. In this way, we neglect a possibly significant effect of close-encounters at low velocity dispersions of “sub-group” scales (see Feldmann et al. 2011).

5 CONCLUSIONS

In this work, we study the evolution of disc galaxies inhabiting a group environment, using controlled collisionless N -body simulations of isolated mergers. Our goal is to estimate the relative contributions of both the global tidal field and close-encounters between group members to the evolution of disc galaxies. We probe a parameter space that covers a number of relevant aspects of the galaxy-group interaction. Regarding the disc galaxies, we explore different initial inclinations (with respect to the disc rotation), different orbital eccentricities (consistent with cosmological simulations), and the presence of a central stellar bulge in the disc. Regarding the population of satellite galaxies in the group, we explore different number of members (consistent with observations of groups), variations in their stellar mass content (also consistent with observations), and variations in the total mass of the satellite population. Our fiducial disc galaxy resembles a bulge-less, slightly less massive Milky Way.

Our main results are the following:

- Close-encounters in a group environment with the most likely number of members are found to be rare and gravitationally weak. Most of the encounters between galaxies occur at separations ~ 50 kpc and relatively late in the simulations, when group members have already lost a sizeable fraction of their initial mass, reducing significantly their capacity to affect gravitationally the disc galaxy. Thus, in our simulations, the *direct* effect of close-encounters between galaxies in groups is much less relevant than the influence of the global tidal field of the group.

- Within the group environment, the influence of other members on a given galaxy is found to be mostly *indirect* by altering the global tidal field, as group members transfer to it mass (via tidal stripping) and energy/angular momentum (via dynamical friction). The mass added to the central region of the group shortens the merger timescale of an infalling galaxy, causing it to experience more structural transformations and mass stripping. On the other hand, the addition of energy/angular momentum provokes a displacement of the densest region of the group, causing a delay in the evolution of an infalling galaxy, as the time between pericentric passages about the group centre increases.

- We find that the evolution of general properties of disc galaxies (such as merger timescale, stellar mass loss, scale-length, mean thickness) caused by other group members is

highly variable, depending mostly on the initial orbital parameters (positions and velocities) of group members. However, the “median” evolution of disc galaxies is found to be reasonably well approximated by the effect only due to the global tidal field (i.e. in absence of close-encounters). Interactions with group members introduce a “scatter” around the “median” evolution of disc galaxies, whose amplitude depends mostly on the combined total mass of the group members, their number and mass distribution.

- Counter-intuitively, disc galaxies can sometimes be *less* affected by environmental effects after interacting with group members, i.e. galaxies can retain their initial structure and mass content for a longer time. The high variability of the properties of disc galaxies due to the influence of group members could also wash out underlying correlations with environmental properties, such as the group mass.

- The effect of the global tidal field combined with close-encounters between galaxies is inefficient at inducing or enhancing the formation of central bulges in stellar discs present at accretion time. This confirms our previous conclusion that, if S0 are formed from spiral galaxies preferentially in group environments, then their often large central bulges should contain mostly relatively young stars in comparison to their stellar discs. This result is found to be consistent with recent observations of S0 galaxies in the Fornax cluster.

- Finally, we find that prescriptions based on simulations that do not account for close encounters (e.g. those done to obtain merger timescales) remain valid and can indeed be used in the framework of galaxy formation models. More sophisticated implementations of those prescriptions could include a scatter dependent e.g. on the total stellar mass, mass distribution and number of nearby galaxies.

In the first two papers of this series we have studied the influence of the global tidal field and that of close-encounters on the evolution of disc galaxies within group environments, estimating their relative contributions. Thus far, we have focused on their effect on the stellar content of galaxies that is already present when disc galaxies are accreted onto a group. In the third paper of this series, we will examine the contribution of the gaseous components of disc galaxies in groups.

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APPENDIX A: SCALELENGTH AND THICKNESS EVOLUTION OF STELLAR DISCS

Figs. A1 and A2 summarise the evolution of the scalelength and mean thickness of disc galaxies in all our experiments. They show the “median” evolution (over different initial orbital distributions of group members), extreme cases, and the disc evolution in the corresponding “control” simulations where group members are not included. Even though the inclusion of a population of group members introduces a significant “scatter” in the structural evolution of disc galaxies, in general the “median” evolution of both the scalelength and mean thickness can be described remarkably well by relatively simpler simulations that do not include group members. This is found to be independent of the initial orbital eccentricity of the disc galaxy, its initial inclination, the presence of a central bulge, the number of group members, the total mass of the population of group members and their stellar mass distribution. The “scatter” in the structural evolution of discs is driven mainly by the total mass of the population of group members, and to a lesser degree by the eccentricity of the orbits.

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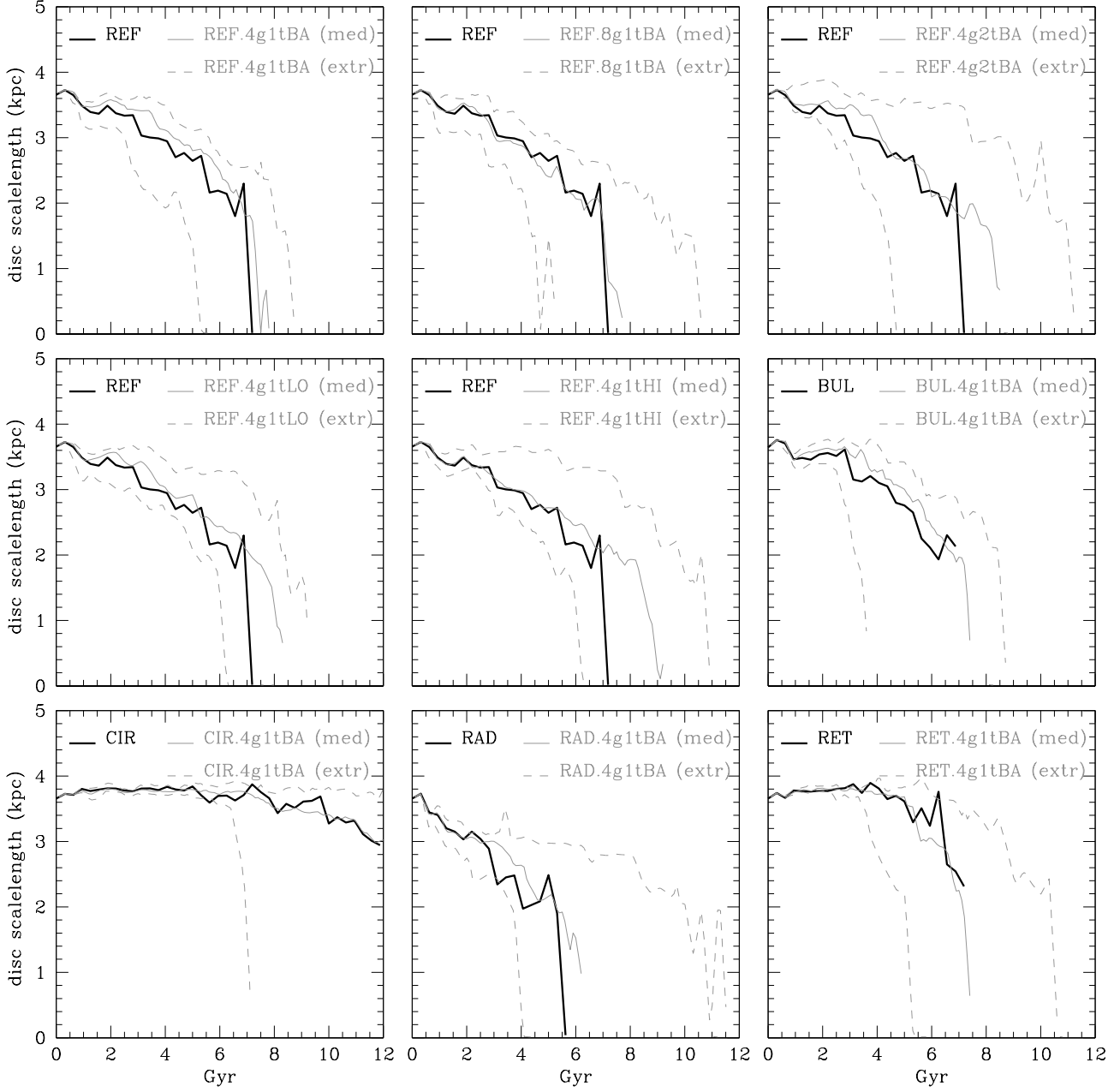


Figure A1. Evolution of the scalelength of stellar discs (since infall until they are disrupted) in experiments covering different properties of the group population (number of members, combined total mass, mass distribution), disc's structure and (initial) orbital parameters of disc galaxies. Each panel compares the median (grey solid) and extreme cases (grey dashed) of the evolution due to the inclusion of group members to the corresponding case when no members are present in the group halo (black).

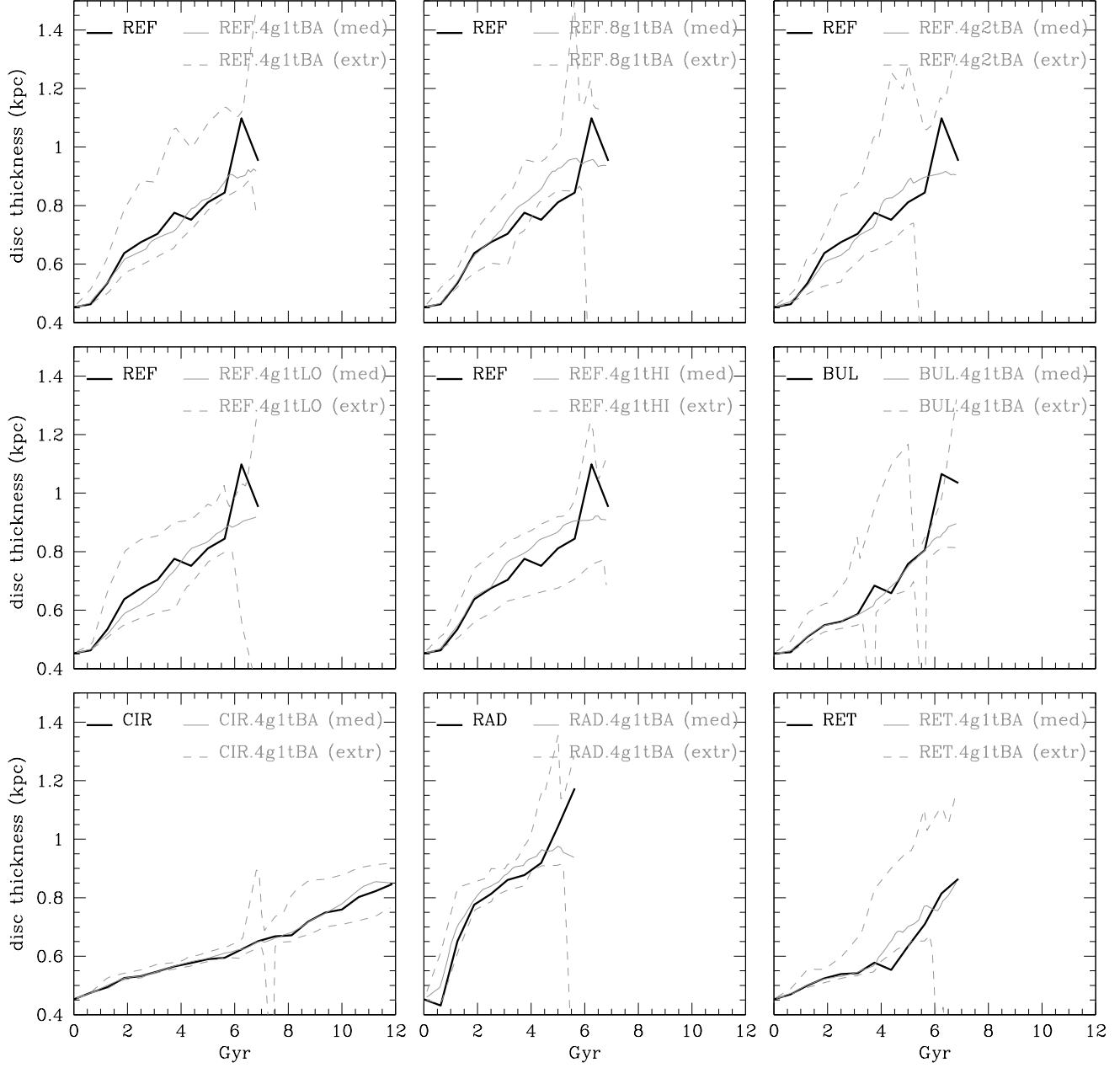


Figure A2. Evolution of the (mean) thickness of stellar discs (since infall until they are disrupted) in experiments covering different properties of the group population (number of members, combined total mass, mass distribution), disc's structure and (initial) orbital parameters of disc galaxies. Each panel compares the median (grey solid) and extreme cases (grey dashed) of the evolution due to the inclusion of group members to the corresponding case when no members are present in the group halo (black).